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FLARES IN LONG AND SHORT GAMMA-RAY BURSTS: A COMMON ORIGIN IN A HYPERACCRETING ACCRETION DISK

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ABSTRACT

Early-time X-ray observations of gamma-ray bursts (GRBs) with the *Swift* satellite have revealed a more complicated phenomenology than was known before. In particular, the presence of flaring activity on a wide range of timescales probably requires late-time energy production within the GRB engine. Since the flaring activity is observed in both long and short GRBs, its origin must be within what is in common for the two likely progenitors of the two classes of bursts: a hyperaccreting accretion disk around a black hole of a few solar masses. Here we show that some of the observational properties of the flares, such as the duration-timescale correlation, and the duration–peak luminosity anticorrelation displayed by most flares within a given burst, are qualitatively consistent with viscous disk evolution, provided that the disk at large radii either fragments or otherwise suffers large-amplitude variability. We discuss the physical conditions in the outer parts of the disk and conclude that gravitational instability, possibly followed by fragmentation, is the most likely candidate for this variability.

Subject headings: accretion, accretion disks — black hole physics — gamma rays: bursts — X-rays: general

1. INTRODUCTION

The launch of the *Swift* satellite has opened a new era of gamma-ray burst (GRB) studies. In addition to fulfilling prelaunch expectations by discovering the afterglows of short GRBs (Gehrels et al. 2005; Hjorth et al. 2005; Fox et al. 2005; Covino et al. 2005) and detecting GRBs at very high redshift (Haislip et al. 2005; Cusumano et al. 2005; Tagliaferri et al. 2005; Kawai et al. 2005), *Swift* has also revealed a new, unexpected phenomenology. *Swift* X-ray Telescope (XRT) observations have shown that the early X-ray afterglow light curves of nearly a half of *Swift* bursts harbor erratic X-ray flares (Burrows et al. 2005; Nousek et al. 2005; O'Brien et al. 2005). Although in some bursts there is only one distinct flare (e.g., GRB 050406; Romano et al. 2005), in other cases there are several flares in each burst (O'Brien et al. 2005). In particular, the X-ray afterglow light curve of the $z = 6.3$ GRB 050904 shows erratic variability with several distinct flares (Cusumano et al. 2005; Watson et al. 2005).

Understanding the origin of the flares is of great theoretical interest, since they trace the activity of the GRB engine. Although the existence of energy injection subsequent to the main GRB phase has been used to argue in favor of magnetic rather than neutrino jet launching (Fan et al. 2005), the origin of reenergizations in the first place remains unclear. For the case of long GRBs, King et al. (2005) suggested that the X-ray flares could be produced from the fragmentation of the collapsing stellar core in a modified hypernova scenario. The fragment subsequently merges with the main compact object formed in the collapse, releasing extra energy. In this two-stage collapse model, the time delay between the burst and the flare reflects the gravitational radiation timescale for the orbiting fragment to be dragged in. For the case of short GRBs, MacFadyen et al. (2005) suggested that the flares could be the result of the interaction between the GRB outflow and a noncompact stellar companion in a model in which short GRBs result from the collapse of a rapidly rotating neutron star in a close binary system.

In this Letter we suggest a new interpretation of the origin of the observed X-ray flares. Our model is motivated by the fact that the flares are observed in both long and short GRBs, which are likely to be associated with different types of progenitors: namely, collapsars for the long GRBs (Stanek et al. 2003; Hjorth et al. 2003) and mergers of compact objects for the short ones (Gehrels et al 2005; Bloom et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Barthelmy et al. 2005; Berger et al. 2005). Unless the similarities between these classes of events are coincidental, the flares are likely to have something to do with what is in common between a GRB triggered by a collapsar and a GRB triggered by a binary merger: an accretion disk rapidly accreting onto a black hole. In the following we argue that the observational properties of the flares are generically consistent with some kind of large-amplitude instability occurring in the outer part of the accretion disk. The origin of such an instability is speculative, but we suggest gravitational instability as one possibility.

2. OBSERVATIONAL PROPERTIES OF THE FLARES

Several observed properties of the flares constrain potential theoretical explanations. The flares typically rise and fall rapidly, with the typical rising and falling timescales usually much shorter than the epoch when the flare occurs. Their arrival time does not appear to correlate with the burst duration T_{90}. The existence of flares is difficult to interpret within the framework of the external shock model and is consistent with a late internal shock origin, which requires late central engine activity after the prompt gamma-ray emission phase is over (Burrows et al. 2005; Zhang et al. 2005). The internal shock model also demands a much smaller energy budget than the external shock model (Zhang et al. 2005). Given the above, we assume henceforth that the flares directly reflect the activity of the GRB engine.

Another qualitative feature is that within a particular burst, the durations of the flares are typically positively correlated with the times when the flares occur. This is evident from the fact that the widths of the flare pulses are more or less similar in logarithmic light curves (O'Brien et al. 2005; Cusumano et

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al. 2005) and that the quantity $\delta t/t_{\rm peak}$ is essentially constant for different flares (e.g., Godet et al. 2005). This is particularly clear for the long GRB 050502B (Falcone et al. 2005) and the short-hard GRB 050724 (Barthelmy et al. 2005). In both cases, there is an early flare (several hundreds of seconds for GRB 050502B and several tens of seconds for GRB 050724) whose duration is of the order of the peak time itself, and there is also a very late flare at several times 10^4 s, with a duration of the same order. The luminosity of the flares appears to scale with the total energy budget of the prompt emission and hence is smaller for the short burst. Apart from this overall normalization, there are no clear differences between flare properties in long and short bursts, although there is only one short burst in which several flares have been observed.

Finally, the peak luminosity of the flares is typically negatively correlated with their arrival time: later flares tend to be less bright than earlier ones. This is particularly evident for the case of GRB 050904 (Watson et al. 2005). The total fluence of the flares also tends to decrease with their arrival time, although to a lesser extent, given their longer duration.

3. A MODEL FOR FLARES IN LONG AND SHORT GRBs

The ultimate source of power in GRBs is believed to be black hole accretion.[3] Whether the accreting material is provided by the envelope of a collapsing star as in the collapsar model (MacFadyen & Woosley 1999) or by the debris of a tidally disrupted companion in binary merger scenarios (Eichler et al. 1989), the outcome is a disk accreting at very high rates. Within the internal shock scenario (e.g., Kobayashi et al. 1997), variability in GRB light curves closely reflects the underlying variability of the inner engine.

The basic physical conditions within GRB disks can be derived by assuming steady state conditions (e.g., Popham et al. 1999; Narayan et al. 2001; Di Matteo et al. 2002). These studies show that at the high accretion rates ($\dot{M} \sim 1 M_\odot$ s^{-1}) needed to provide the GRB luminosity, the disk cannot cool efficiently, and a large fraction of it is advection-dominated. Furthermore, especially in the high-temperature inner regions, neutrinos play a major role in providing cooling for the disk. Janiuk et al. (2004) extended these steady state studies by following the time-dependent evolution of a neutrino-dominated accretion disk, as its fuel supply dwindles and its accretion rate drops. Their calculations showed that, after the material replenishing the disk is exhausted, the accretion rate and resulting engine power drop rapidly. A rapid drop of the energy deposition rate was also found by Setiawan et al. (2004) by means of hydrodynamic simulations. The observed flares demonstrate that, while this picture may hold for the main GRB phase, it can fail at late times. We argue below that the observed flare properties are suggestive of reenergization by blobs of material that make their way from a range of initial distances toward the accreting black hole.

The properties of the GRB disk, and in particular the main cooling processes, are highly dependent on the mass accretion rate; for a given accretion rate, they further depend on the radial location within the disk (e.g., Narayan et al. 2001; Di Matteo et al. 2002, hereafter DPN) and on the composition that affects the opacity (Menou et al. 2001). However, for given disk properties, there exists a typical timescale, the viscous time

$$t_0(R) = \frac{R^2\Omega_{\rm K}}{\alpha c_s^2} \quad (1)$$

that sets the typical duration of the accretion phase for a ring of material initially at a distance R from the accreting object. In the above equation, $\Omega_{\rm K}$ is the Keplerian velocity of the gas in the disk, c_s is the sound speed of the accreting material, and α is a parameter characterizing the strength of viscosity (Shakura & Sunyaev 1973). The dependence of t_0 with R changes depending on the characteristics of the disk. If advection dominates, as found by DPN for accretion rates $\dot{M} \gtrsim 1\ M_\odot$ s^{-1}, then the disk scale height $H = c_s/\Omega_{\rm K}$ is $\sim R$, and the viscous timescale can be approximated as

$$t_0 \sim \frac{1}{\alpha\Omega_{\rm K}} \sim 5 \times 10^{-4}\alpha_{-1}^{-1} m_3 r^{3/2}\ {\rm s}, \quad (2)$$

where $m_3 = M/(3\ M_\odot)$, $r = R/R_{\rm S}$; $R_{\rm S}$ is the Schwarzschild radius. The viscosity parameter has been written in units of $\alpha_{-1} \equiv \alpha/0.1$. At a distance of $r \sim 1000$, the accretion time is $\sim 15 m_3 \alpha_{-1}^{-1}$ s.

Evidently, the viscous timescales associated with the very high $\dot{M}$, advection-dominated flow, are short compared to some of the observed flare timescales at any reasonable radii. However, at large radii and/or late times, the disk will have a smaller accretion rate. As the accretion rate decreases, the fraction of advected energy also decreases, and the disk cools more efficiently, implying $H < R$. A smaller H/R ratio increases the accretion time t_0 by a factor of $(H/R)^{-2}$. This can be substantial. In the limit of a standard Shakura-Sunyaev disk (which will not, we emphasize, be attained during the time interval of interest here), H/R is of the order of 10^{-2} in the region at $r \sim 10^3$ that is dominated by gas pressure and electron scattering opacity. If we assume that later-time flares arise from significantly depleted disks, whose accretion rate is not high enough to make the disk substantially advection-dominated, then accretion times of 10^4 s from material at $r > 10^3$ are not unreasonable. Depending on the conditions then, the accretion timescales from fragments of material originally in the outer parts of the disk can vary between tens of seconds to several thousands of seconds, with the longer timescales obviously deriving from the outermost rings of material.

How the derived accretion timescale relates to the observable delays between the initial event and subsequent flares depends on the state of the disk material. If the disk develops a ringlike structure, but otherwise remains continuous, then the arrival time of a ring of material initially at a distance R is simply of the order of $t_0(R)$. Once this ring begins to accrete, the duration of the main (i.e., most intense) accretion phase is also on the order of $\sim t_0$. After a time $t \sim t_0$, the accretion rate drops abruptly (see, e.g., numerical simulations by Cannizzo et al. 1990). Therefore, this scenario predicts that the arrival time of each new flare should directly correlate with its total duration. The sudden cessation of the jet power (i.e., accretion power) would also leave imprints on the light curve by means of a rapid decay of flux, by means of the so-called curvature effect (Kumar & Panaitescu 2000; Zhang et al. 2005). Such rapid decays have been indeed seen in the postflare light curves of many bursts (e.g., Falcone et al. 2005; Barthelmy et al. 2005). Moreover, the accretion rate of a ring of initial mass $M(t_0)$ is of the

[3] We note that in scenarios in which the role of the accretion flow is primarily to tap into the spin energy of the black hole—for example, via the Blandford-Znajek (1977) mechanism—then the net magnetic flux carried inward by the flow is at least as important as the mass accretion rate itself.

order of $\dot{M}(t_0) \propto M(t_0)/(t_0)$ during the time t_0. If the initial masses of the fragments are not hugely different (or at least the outermost ones are not substantially more massive than the innermost ones), then the peak luminosity of the flares should decline with their arrival times. This again reflects the general behavior seen in the observed flares. The total energy (proportional to the fluence) released in each flare is proportional to the total mass of the fragment that caused that episode of activity.

Alternatively, it is possible that the disk—in its outer regions—does not remain a continuous fluid but rather fragments into one or more bound objects. This does not alter the generic behavior discussed above but does alter the expected timescales. In particular, if most of the mass at large radii is bound up in fragments, then the timescale for those objects to be dragged into the black hole via viscous effects is lengthened by a factor of the order of $(M_{\rm frag}/M_{\rm disk}) > 1$, where $M_{\rm disk}$ is the exterior disk mass (Syer & Clarke 1995). This could permit substantially longer timescales for any given radius. Furthermore, since in a fragmentation scenario new fuel for the central engine would be provided via tidal disruption of the fragments (at a radius smaller than the initial fragmentation radius), the duration of bursts of accretion would be shortened. We might expect to observe shorter flares, separated by relatively longer intervals between flares.

4. DISK FRAGMENTATION BY GRAVITATIONAL INSTABILITIES

The observed characteristics of the X-ray flares seen in several GRB light curves are consistent with their being produced by large changes in the inner accretion rate that are controlled by the viscous timescale at large distances from the black hole. This immediately begs the question of what are the important processes in the outer disk that drive such variability. The picture we start with is the one developed through numerical studies of progenitor models: whether as a result of the collapse of a massive star (see MacFadyen & Woosley 1999) or as a result of the merger of two compact objects (e.g., Ruffert & Janka 2001; Rosswog et al. 2004; Lee et al. 2005), a massive, rapidly accreting disk is formed. The physical conditions within these disks are fairly similar, irrespective of their origin. In particular, while the total energy output of short bursts is at least a factor of 10 smaller than that of the long ones, the peak luminosities in the two classes of objects are comparable (Gehrels et al. 2005; Villasenor et al. 2005; Barthelmy et al. 2005). This suggests that, while the total mass of the initial accretion disk is likely to be smaller for the short bursts, the accretion rates during the prompt phase are comparable for the two classes of bursts and can range from 1/10 $M_\odot$ s^{-1} or so to several times 1 $M_\odot$ s^{-1}.

Several classes of known disk instabilities could, in principle, lead to large variations in the accretion rate onto the black hole (as noted above, the seat for these instabilities must lie in the outer disk from timescale arguments). Thermal instability occurs when $(d \ln Q^+/d \ln T)_\Sigma > (d \ln Q^-/d \ln T)_\Sigma$, where Q^- and Q^+ are the cooling and heating rates, respectively, and Σ is the surface density of the disk, while if $d\dot{m}/d\Sigma < 0$, the disk would be viscously unstable. Thermal instability, in particular, is known to lead to very large amplitude outbursts, for example, in dwarf novae. However, a stability analysis of the GRB disk models by DPN suggested that these disks are thermally and viscously stable throughout their entire radial extent, so these instabilities do not appear promising as explanations for flares. Also disfavored are *small-scale* intrinsic instabilities, whether associated with MHD turbulence (De Villiers et al. 2003) or with shock instabilities associated with the photodisintegration of α-nuclei (MacFadyen & Woosley 1999). Although variability associated with these processes is inevitable—and likely responsible for the variability in the accretion rate necessary to explain the variable luminosity of the GRB prompt emission—they do not yield large-scale coherent flares as apparently required to match observations.

A better, although still speculative, possibility is gravitational instability, especially if that instability results in actual fragmentation of the disk. The accretion flow will become gravitationally unstable if the Toomre parameter (Toomre 1964)

$$Q_{\rm T} = \frac{c_s \kappa}{\pi G \Sigma} < 1, \tag{3}$$

where c_s is the sound speed and κ is the epicyclic frequency. This may occur in the outer regions. DPN found that a gravitationally unstable region ($Q_{\rm T} \sim 1$) is possible for $R \gtrsim 10^2 R_{\rm S}$ if the accretion rate is high enough (of the order of $\dot{M} \gtrsim 3\ M_\odot$ s^{-1}) at those radii. For accretion flows arising from collapsars, this requires at a minimum that the specific angular momentum of infalling matter be $j \gtrsim 2 \times 10^{17}$ cm^2 s^{-1} (for a 3 $M_\odot$ central object), which is possible if the collapse results from a relatively rapidly rotation stellar core. Producing a sufficiently massive disk at large radii as a consequence of a merger of compact objects is likely to be harder, since at least initially the relatively low specific angular momentum implies that $Q_{\rm T,\,min} \sim 10$ (Lee et al. 2005). This might suggest that fragmentation is more likely in the case of GRB's whose progenitors are collapsars, whereas disks from the merger of compact object are more likely to remain continuous. However, since observationally flares in the two classes of GRBs appear to be similar (although, as noted previously, the observational sample for the short GRBs is very limited), a common mechanism for both types is favored. In fact, binary merger simulations by Setiawan et al. (2004) show that, for an initial disk mass on the order of a tenth of a solar mass or so, the peak accretion rate can become as high as $\dot{M} \sim 10\ M_\odot$ s^{-1} or more. Under these conditions, gravitational instability could occur at a few tens of Schwarchild's radii (DPN). Moreover, three-dimensional simulations of coalescing neutron stars by Ruffert & Janka (2001) show that a substantial mass of material gains angular momentum as a consequence of tidal effects and moves to larger radii (indeed, in their models, up to ∼30% of the total mass in the disk actually becomes unbound). Therefore, although less likely than for the collapsar model, it is possible that the conditions for the onset of the gravitational instability might also occur within disks produced by mergers of compact objects. In this case, instability seems most likely to occur as an expanding flow reaches the larger radii where gravitational instability is inevitable.

Once a gaseous disk becomes gravitationally unstable, two classes of behavior are possible. First, the disk may develop a quasi-steady spiral structure—which acts to transport angular momentum outward and mass inward. This mode of gravitational instability can drive large-amplitude outbursts of accretion if the disk mass is sufficiently large (Laughlin et al. 1998; Lodato & Rice 2005; Vorobyov & Basu 2005). Second, the disk may fragment into bound objects. Fragmentation is inevitable if the local cooling time

$$t_{\rm cool} < t_{\rm crit} \approx 3\Omega_{\rm K}^{-1}, \tag{4}$$

in which case the maximum stress obtainable from gravitational instability (roughly $\alpha_{\max} \sim 0.1$) produces insufficient heating to offset cooling (Gammie 2001; Rice et al. 2003). For a collapsar disk in its early, advection-dominated phase, we expect that the cooling timescale, dominated at these radii by neutrino emission, will be comparable to the viscous timescale $t_0 \sim \alpha^{-1}\Omega_K^{-1}$. For $\alpha = 0.1$, the disk is therefore nominally stable against fragmentation, although not by such a margin that details of the problem (such as the presence of cooling via photodisintegration) might not change the answer. Fragmentation may also be possible, even for longer cooling timescales, if infall adds mass to the disk on a timescale shorter than the minimum viscous timescale $t_0 \sim (H/R)^{-2}\alpha_{\max}^{-1}\Omega_K^{-1}$.

If fragments form, their initial mass $M_{\rm frag} \sim \Sigma(2H)^2$ is set by local disk properties. However, such fragments will accrete and/or merge rapidly, until their tidal influence on the surrounding disk manages to open a gap. This occurs at a mass (Takeuchi et al. 1996)

$$M_{\rm frag} \simeq \left(\frac{H}{R}\right)^2 \alpha^{1/2} M, \quad (5)$$

where M is the central object mass. If the disk fragments in the early, advection-dominated phase where $H \sim R$, we would expect rather massive fragments, whereas fragmentation taking place at larger radii and/or later times would give rise to lower mass objects.

5. SUMMARY

Early X-ray observations *Swift* have revealed a new, rich, and unexpected phenomenology of GRBs. The observation of energetic flares occurring tens of seconds to tens of thousands of seconds after the initial burst signals the presence of energy injection long after the prompt phase is over. Flares are an important diagnostic of the GRB engine. In this Letter we have noted how the observed positive correlation between the arrival time and duration of the flares, and the negative correlation of their peak luminosity with duration (which most flaring episodes within a given burst display), can be interpreted. Generically, these observations are consistent with a model in which the flares are due to blobs of material that initially circularize at various radii and subsequently evolve viscously. Since the flares are seen in both long and short GRBs, and these are likely to be produced by different progenitors, we have suggested that these fragments of material are likely to be created within the initial, hyperaccreting accretion disk. In particular, we have noted how, in the outer parts of these disks, the physical conditions may be suitable for gravitational instability, leading either to large-amplitude changes in the inner accretion rate or complete fragmentation of the disk followed by a relatively slow in-spiral of the fragments toward the black hole.

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